

BICEP2, the Higgs Mass and the SUSY-breaking Scale

Luis E. Ibáñez and Irene Valenzuela

*Departamento de Física Teórica and Instituto de Física Teórica UAM-CSIC,
Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain*

Recent BICEP2 results on CMB polarisation B-modes suggest a high value for the inflation scale $V_0^{1/4} \simeq 10^{16}$ GeV, giving experimental evidence for a physical scale in between the EW scale and the Planck mass. We propose that this new high scale could be interpreted as evidence for a high SUSY breaking scale $M_{ss} \simeq 10^{12} - 10^{13}$ GeV. We show that such a large value for M_{ss} is consistent with a Higgs mass around 126 GeV. We briefly discuss some possible particle physics implications of this assumption.

I. INTRODUCTION

The BICEP2 collaboration has recently reported the measurement of cosmological B-mode polarisation in the CMB [1]. The observed tensor to scalar ratio $r = 0.20^{+0.07}_{-0.05}$ is unexpectedly large. Since r is related to the energy scale of inflation V_0 by

$$V_0^{1/4} \simeq 2 \times 10^{16} \left(\frac{r}{0.20} \right)^{1/4} \text{ GeV} \quad (1)$$

these data give first experimental evidence for the existence of a new physics scale in between the EW and Planck scales. This fact, if indeed confirmed, has important implications for particle physics. The value of V_0 could suggest this scale could have something to do with a GUT scale $M_X \simeq 10^{16}$ GeV. On the other hand, if one thinks that SUSY is a fundamental symmetry of the SM which is spontaneously broken at some scale, one could think that the height of the inflation potential could be of the same order as the height of the SUSY breaking scalar potential. In particular the latter is expected to be of order

$$V_{ss} \simeq (m_{3/2} M_p)^2 \quad (2)$$

with $m_{3/2}$ the gravitino mass, which also gives us the typical size of SUSY breaking soft terms. Then the BICEP2 results could be pointing to a SUSY breaking scale

$$M_{ss} \simeq \frac{V_0^{1/2}}{M_p} \simeq 10^{13} \text{ GeV} . \quad (3)$$

Specifically, the simplest inflation model in agreement with BICEP2 data is given by the simple chaotic inflationary model [2] with

$$V_I = \frac{m_I^2}{2} \phi^2 . \quad (4)$$

The inflation mass m_I in chaotic inflation, in which ϕ reaches M_p at inflation would be of order 10^{13} GeV. It could also be slightly lower, $m_I \simeq 10^{12}$ GeV, if, e.g., one takes into account possible corrections coming from $\text{dim} > 4$ polynomials in ϕ , see e.g.[3]. In the present scheme, the inflaton mass parameter could be generated by broken SUSY, suggesting $M_{ss} \simeq m_I \simeq 10^{12} - 10^{13}$ GeV. Note that we are not claiming that low energy SUSY, with soft terms at the TeV scale is in conflict with the BICEP2 results. Only that it would require the height of the inflaton potential to be much higher than the SUSY-breaking scalar potential. This may lead to problems e.g. in scenarios in which there are moduli whose vevs are fixed upon SUSY breaking, see e.g.[4].

In what follows we will assume that the BICEP2 results are indeed pointing to a SUSY-breaking scale $M_{ss} \simeq 10^{12} - 10^{13}$ GeV and derive some consequences. In particular its consistency with the observed Higgs mass value. See [5, 6] for other recent papers on implications of the BICEP2 results.

II. INTERMEDIATE SUSY BREAKING SCALE AND HIGGS MASS

If this new scale is present, the EW hierarchy problem becomes even more pressing, since loops involving the heavy states associated to the new scale will presumably give quadratic large contributions to the Higgs mass which cannot be ignored. On the other hand, with SUSY broken at such high scales [7], it will not be relevant for the solution to the hierarchy problem. It seems then that the Higgs mass should be somehow fine-tuned to survive at low-energies. There are however additional reasons to

believe that a SUSY extension of the SM could still apply at some energy scale, though possibly a very large one. In particular, supersymmetry is a built-in symmetry inside string theory, which is the leading candidate for an ultraviolet completion of the SM, including gravity. Also a SUSY version of the standard model guarantees stability (absence of tachyons) for the abundant scalars appearing in generic string compactifications. On the other hand the existence of a string landscape may provide a rationale for understanding the origin of fine-tuning.

Irrespective of any string theory arguments, having SUSY at some (possibly large) scale may solve the stability problem of the Higgs scalar potential. Indeed, if one extrapolates the value of the Higgs SM self-coupling λ up in energies according to the RGE, the top quark loops make it to vanish and then become negative at scales of order $10^{11} - 10^{12}$ GeV, signalling an instability (or metastability) of the Higgs scalar potential at very high energies [8, 9]. If SUSY is restored around those energies, the Higgs potential is automatically stabilised, since a SUSY potential is always positive definite. In addition to stabilising the Higgs vacuum, high scale SUSY breaking may provide an understanding of the observed value of the Higgs mass [10–13] (see also [14, 15]). Specifically, in [12] it was shown that, a SUSY breaking scale above 10^{10} GeV generically gives rise to values $m_H = 126 \pm 3$ GeV for the Higgs. Let us see how this comes about. Let us assume for simplicity that above a large SUSY-breaking scale M_{ss} one recovers the MSSM structure. The Higgs sector then has a general mass matrix

$$\begin{pmatrix} H_u & H_d^* \end{pmatrix} \begin{pmatrix} m_{H_u}^2(Q) + \mu^2(Q) & m_3^2(Q) \\ m_3^2(Q) & m_{H_d}^2(Q) + \mu^2(Q) \end{pmatrix} \begin{pmatrix} H_u^* \\ H_d \end{pmatrix} \quad (5)$$

where Q is the running scale, and μ is a standard MSSM mu-term. For a SM Higgs boson to remain light below the M_{ss} scale one has to fine-tune

$$\det(M_H^2(M_{ss})) = 0. \quad (6)$$

This could happen if, at a unification scale $Q = M_X$ the mass matrix has only positive eigenvalues and then at the lower running scale $Q = M_{ss}$ the determinant vanishes. The fine-tuning condition is

$$(m_{H_u}^2(M_{ss}) + \mu^2(M_{ss}))(m_{H_d}^2(M_{ss}) + \mu^2(M_{ss})) = m_3^4(M_{ss}) \quad (7)$$

and then one can check that the linear combination $H_{SM} = \sin\beta H_u + \cos\beta H_d^*$ remains light and becomes

the SM Higgs field. Here the mixing angle is given by

$$\tan\beta(M_{ss}) = \left| \frac{m_{H_d}^2(M_{ss}) + \mu^2(M_{ss})}{m_{H_u}^2(M_{ss}) + \mu^2(M_{ss})} \right|^{1/2}, \quad (8)$$

while the Higgs self-coupling at M_{ss} is given by the *MSSM* boundary condition [7, 16]

$$\lambda_{SUSY}(M_{ss}) = \frac{1}{4}(g_2^2(M_{ss}) + g_1^2(M_{ss})) \cos^2 2\beta(M_{ss}). \quad (9)$$

A natural additional condition to impose is that $m_{H_u} = m_{H_d}$ at the unification scale M_X . This happens in a variety of models including most GUT's and string theory frameworks. Note that one then has $\tan\beta = 1$ at the unification scale, but it runs to a value $\tan\beta > 1$ at M_{ss} . Still $\cos^2 2\beta$ remains small, explaining why the Higgs self-coupling is close to zero at scales $M_{ss} > 10^{10}$ GeV. One can compute the value of $\tan\beta$ at M_{ss} by running it down to the M_{ss} scale. The computation turns out to be quite independent on the choice of soft terms for the running, as long as they are all of the same order of magnitude. There is a mild dependence on the μ parameter that we will show explicitly below. One can then obtain the value of the self-coupling in eq.(9) by inserting the value so obtained for β . The EW gauge couplings $g_{1,2}^2(M_{ss})$ are obtained running up their experimental value from the EW scale. Once we know the value of $\lambda_{SUSY}(M_{ss})$, one can then finally run it down to the EW scale and compute the Higgs mass from $m_H^2(Q_{EW}) = 2v^2(\lambda(Q_{EW}))$, see [12] for the relevant RGE, thresholds and other details.

III. RESULTS

In the present case we are identifying M_{ss} with the value of $V_0^{1/2}/M_p$ suggested by BICEP2 data. We have performed a computation of the value of the Higgs mass under the assumption that this is the SUSY breaking scale and that $\tan\beta = 1$ at the unification scale. The unification scale is fixed by identifying it with the scale at which the g_2 and g_3 SM gauge couplings unify, assuming there are threshold corrections which make them consistent also with unification with g_1 . The required threshold corrections may come from a variety of sources. For example, if the $U(1)_Y$ slightly mixes with a hidden $U(1)$ the hypercharge normalisation slightly changes in the correct direction, see e.g. [19, 20]. The resulting

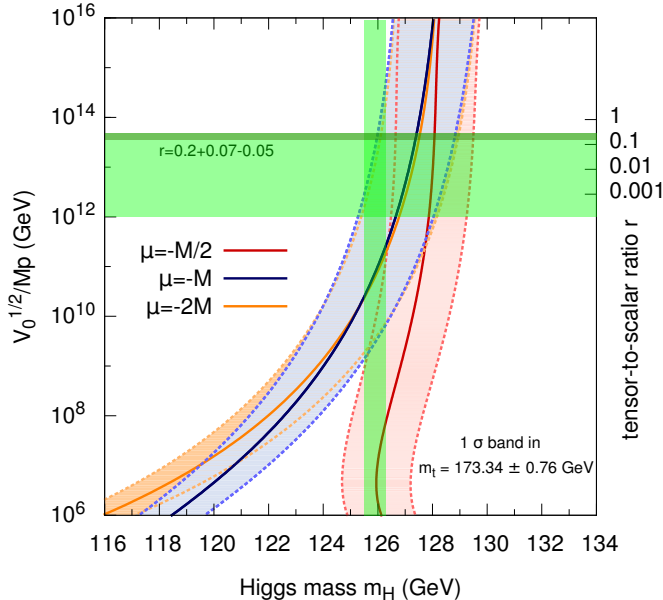


FIG. 1. The scale $M_{ss} = m_I \simeq V_0^{1/2}/M_p$ versus the Higgs mass computed for three values of μ . The bands correspond to results using the one sigma values for $m_{top} = 173.3 \pm 0.7$ from the LHC+Fermilab average [17]. The vertical band gives the measured Higgs mass at LHC [18]. The thin horizontal line corresponds to the SUSY breaking scale $V_0^{1/2}/M_p$ obtained from the observed tensor ratio r using eq.(1).

unification scale is $M_X = 10^{16}$, also consistent with the BICEP2 results for $V_0^{1/4}$. In our computation we have performed the running of gauge and Higgs couplings at two loops, and the running of the soft terms in the range $M_{ss} - M_X$ to one loop. We also included SM threshold corrections at the EW scale and soft terms dependent threshold corrections at M_{ss} , see [12] for details of the required computation as well as references.

The results obtained are shown in fig.1. The vertical band shows the 1σ values for $m_H = 125.9 \pm 0.4$ [18]. The horizontal thin band corresponds the the SUSY breaking scale $V_0^{1/2}/M_p$ computed from eq.(1) in terms of the tensor ratio r . The wider horizontal line extending it to 10^{12} GeV allows from uncertainties from e.g. $\dim > 5$ operators. For the computation of $\tan\beta$ we have chosen for definiteness universal soft parameters $m_0^2 = |M|^2/2, A = -3M/2$ with M the gaugino mass, although the results are quite insensitive to the soft term structure. There is however a sizable depen-

dence on the Higgs μ -parameter, and we display results for $\mu = -2M, -M, -M/2$ (the sign has negligible impact in the results though). One sees that for a value of the top-quark within 1σ of the LHC-Fermilab average [17], indeed *the Higgs mass is consistent with the measured value of the potential energy at inflation being related to the SUSY breaking scale as $M_{ss} = V_0^{1/2}/M_p$* . This is the main result of this note.

IV. FINAL COMMENTS

If the scheme here proposed is correct, it would seem that the SUSY breaking scale would be about the maximum one compatible with the restoration of the Higgs potential stability. If M_{ss} had been higher than $\simeq 10^{13} - 10^{14}$ GeV, a Higgs minimum lower than the SM one would have developed. But the fact that M_{ss} is so high makes the inflation energy V_0 high enough so as to leave a sizeable imprint in the tensor modes of the CMB. We would have been quite lucky, a lower value for M_{ss} would have made the tensor modes undetectable. So although such a large M_{ss} scale would have made SUSY undetectable at LHC, at least it could have left its imprint in the CMB.

Let us close this note with a few comments on additional implications of the existence of a such large SUSY-breaking scale $M_{ss} \simeq 10^{12} - 10^{13}$ GeV. The fact that the extrapolated Higgs boson self-coupling λ approaches zero (if one includes 2σ errors for the top-quark mass) not far from the Planck scale, and that the corresponding β function is also numerically close to zero at those scales, has been suggested as a hint for a conformal symmetry at the Planck scale [21]. The observation of BICEP2 points to a new fundamental mass scale below M_p , making that possibility unlikely. On the other hand large intermediate scales have been considered in particle physics in a variety of contexts. In particular a Majorana right-handed neutrino mass of the same order $\simeq 10^{12} - 10^{13}$ GeV, would be consistent with appropriate sea-saw neutrino masses for the left-handed neutrinos. In a different vein, in a scheme with such a large SUSY mass, the neutralinos are not available to become the dark matter in the universe. A natural candidate in this situation would be an axion. In fact the BICEP2 measurements

strongly constraint also the allowed axion decay constant f_a . In particular high scale CDM axions with $f_a > 10^{14}$ GeV would be ruled out. Such axions would create large isocurvature fluctuations which are severely constrained by Planck data [6]. Finally, the existence of a mass scale $V_0 \simeq (10^{16})^4 \text{GeV}^4 \simeq M_X^4$, with M_X the unification scale, makes plausible the generation of proton decay operators which could lead to detectable signatures at underground experiments.

While this connection between the Higgs mass and the inflation scale is very attractive, it remain mysterious how a simple polynomial scalar potential with ultra-Planck field values can make sense in a putative ultraviolet completion of the theory. In particular, in the context of string theory there are two new mass scales which are the compactification scale M_c and the string scale M_s . In the simplest situations those two scales are very close and of order the unification scale, $M_X \simeq M_c \lesssim M_s \ll M_p$

(see e.g. [22] for a discussion of these). Above a scale of order 10^{16} GeV a 4D field theory no longer makes sense and one cannot ignore, at least in principle, the KK and string excitations. Thus the apparent success of such simple field theory scalar potentials is somewhat surprising in the string context. The BICEP results are giving us invaluable information which hopefully will shed light on the UV completion of the SM.

ACKNOWLEDGMENTS

We thank P.G. Cámara, V. Diaz and F. Marchesano for useful discussions. This work has been supported by the ERC Advanced Grant SPLE under contract ERC-2012-ADG-20120216-320421 and by the grants FPA 2009-09017, FPA 2009-07908, and FPA 2010-20807-C02. We also thank the spanish MINECO *Centro de excelencia Severo Ochoa Program* under grant SEV-2012-0249. I.V. is supported through the FPU grant AP-2012-2690.

-
- [1] P. A. R. Ade *et al.* [BICEP2 Collaboration], “BICEP2 I: Detection Of B-mode Polarization at Degree Angular Scales,” arXiv:1403.3985 [astro-ph.CO].
 - [2] A. D. Linde, “Chaotic Inflation,” Phys. Lett. B **129** (1983) 177.
 - [3] X. Calmet and V. Sanz, “Excursion into Quantum Gravity via Inflation,” arXiv:1403.5100 [hep-ph].
 - [4] R. Kallosh and A. D. Linde, “Landscape, the scale of SUSY breaking, and inflation,” JHEP **0412** (2004) 004 [hep-th/0411011].
 - [5] K. Nakayama and F. Takahashi, “Higgs Chaotic Inflation and the Primordial B-mode Polarization Discovered by BICEP2,” arXiv:1403.4132 [hep-ph]; A. Kehagias and A. Riotto, “Remarks about the Tensor Mode Detection by the BICEP2 Collaboration and the Super-Planckian Excursions of the Inflaton Field,” arXiv:1403.4811 [astro-ph.CO]; T. Kobayashi and O. Seto, “Polynomial inflation models after BICEP2,” arXiv:1403.5055 [astro-ph.CO]; K. Harigaya and T. T. Yanagida, “Discovery of Large Scale Tensor Mode and Chaotic Inflation in Supergravity,” arXiv:1403.4729 [hep-ph]; K. Harigaya, M. Ibe, K. Schmitz and T. T. Yanagida, “Dynamical Chaotic Inflation in the Light of BICEP2,” arXiv:1403.4536 [hep-ph]; M. P. Hertzberg, “Inflation, Symmetry, and B-Modes,” arXiv:1403.5253 [hep-th].
 - [6] T. Higaki, K. S. Jeong and F. Takahashi, “Solving the Tension between High-Scale Inflation and Axion Isocurvature Perturbations,” arXiv:1403.4186 [hep-ph]; L. Visinelli and P. Gondolo, “Axion cold dark matter in view of BICEP2 results,” arXiv:1403.4594 [hep-ph]; D. J. E. Marsh, D. Grin, R. Hlozek and P. G. Ferreira, “Tensor Detection Severely Constrains Axion Dark Matter,” arXiv:1403.4216 [astro-ph.CO].
 - [7] L. J. Hall and Y. Nomura, “A Finely-Predicted Higgs Boson Mass from A Finely-Tuned Weak Scale,” JHEP **1003** (2010) 076 [arXiv:0910.2235 [hep-ph]].
 - [8] J. A. Casas, J. R. Espinosa and M. Quirós, “Improved Higgs mass stability bound in the standard model and implications for supersymmetry,” Phys. Lett. B **342** (1995) 171; [hep-ph/9409458]; “Standard Model stability bounds for new physics within LHC reach,” Phys. Lett. B **382** (1996) 374. [hep-ph/9603227]; G. Isidori, G. Ridolfi and A. Strumia, “On the metastability of the standard model vacuum,” Nucl. Phys. B **609** (2001) 387 [hep-ph/0104016].
 - [9] J. Elias-Miro, J. R. Espinosa, G. F. Giudice, G. Isidori, A. Riotto and A. Strumia, “Higgs mass implications on the stability of the electroweak vacuum,” Phys. Lett. B **709** (2012) 222 [arXiv:1112.3022 [hep-ph]]; G. Degrandi, S. Di Vita, J. Elias-Miro, J. R. Espinosa, G. F. Giu-

- dice, G. Isidori and A. Strumia, “Higgs mass and vacuum stability in the Standard Model at NNLO,” JHEP **1208** (2012) 098 [arXiv:1205.6497 [hep-ph]]; D. Buttazzo, G. Degrandi, P. P. Giardino, G. F. Giudice, F. Sala, A. Salvio and A. Strumia, “Investigating the near-criticality of the Higgs boson,” JHEP **1312** (2013) 089 [arXiv:1307.3536];
- [10] A. Hebecker, A. K. Knochel and T. Weigand, “A Shift Symmetry in the Higgs Sector: Experimental Hints and Stringy Realizations,” JHEP **1206**, 093 (2012) [arXiv:1204.2551 [hep-th]].
- [11] L. E. Ibáñez, F. Marchesano, D. Regalado and I. Valenzuela, “The Intermediate Scale MSSM, the Higgs Mass and F-theory Unification,” JHEP **1207** (2012) 195 [arXiv:1206.2655 [hep-ph]].
- [12] L. E. Ibáñez and I. Valenzuela, “The Higgs Mass as a Signature of Heavy SUSY,” JHEP **1305** (2013) 064 [arXiv:1301.5167 [hep-ph]].
- [13] A. Hebecker, A. K. Knochel and T. Weigand, “The Higgs mass from a String-Theoretic Perspective,” Nucl. Phys. B **874** (2013) 1 [arXiv:1304.2767 [hep-th]].
- [14] L. J. Hall and Y. Nomura, “Grand Unification and Intermediate Scale Supersymmetry,” JHEP **1402** (2014) 129 [arXiv:1312.6695 [hep-ph]].
- [15] M. Ibe, S. Matsumoto and T. T. Yanagida, “Flat Higgs Potential from Planck Scale Supersymmetry Breaking,” arXiv:1312.7108 [hep-ph].
- [16] N. Arkani-Hamed and S. Dimopoulos, “Supersymmetric unification without low energy supersymmetry and signatures for fine-tuning at the LHC,” JHEP **0506** (2005) 073 [hep-th/0405159].
- [17] “First combination of Tevatron and LHC measurements of the top-quark mass”, ATLAS, CDF, CMS and D0 collaborations, arXiv:1403.4427[hep-ex].
- [18] Particle Data Group, <http://pdg.lbl.gov/2012/reviews/rpp2012-rev-higgs-boson.pdf>.
- [19] R. Tatar and T. Watari, “GUT Relations from String Theory Compactifications,” Nucl. Phys. B **810** (2009) 316 [arXiv:0806.0634 [hep-th]].
- [20] P. G. Cámara, L. E. Ibáñez and F. Marchesano, “RR photons,” JHEP **1109** (2011) 110 [arXiv:1106.0060 [hep-th]].
- [21] F. Bezrukov, M. Y. Kalmykov, B. A. Kniehl and M. Shaposhnikov, “Higgs boson mass and new physics,” [hep-ph/1205.2893]; D.L. Bennett, H.B. Nielsen and I. Picek, Phys.Lett.B 2081988275; C.D. Froggatt and H.B. Nielsen, Phys.Lett.B 368199696; M. Shaposhnikov and C. Wetterich, “Asymptotic safety of gravity and the Higgs boson mass,” Phys. Lett. B 683 (2010) 196 [hep-ph/0912.0208]; M. Holthausen, K. S. Lim and M. Lindner, “Planck scale Boundary Conditions and the Higgs Mass,” JHEP 1202 (2012) 037 [arXiv:1112.2415].
- [22] L.E. Ibáñez and A. Uranga, *String Theory and Particle Physics. An Introduction to String Phenomenology*. Cambridge U.P., (2012).